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Simultaneous Multi-Pipe Failure Impact on Reliability of Water Distribution Systems

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Abstract

Hydraulic reliability assessment of a water distribution system (WDS) can be performed at different states considering various combinations of pipe failures. Current reliability techniques are mostly restricted to lower sates of reliability considering just one pipe failure at a time. In this study, multi-criteria decision analysis (MCDA) approach is applied to rank a set of distribution layouts (alternatives) using various states of reliabilities (criteria). Results show that multi-state reliability assessment (MSRA) of a WDS may lead to completely different and more comprehensive results since considering various states of reliability at the same time.

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Keywords: Water distribution system, multi-criteria decision analysis, reliability.

1. Introduction

Continuous delivery of water to consumers of a water distribution system (WDS) may be interrupted in some circumstances due to occurrence of a component failure. Failure may undermine the hydraulic integrity of a WDS. Consequently, consumers may be supplied partially (if not at all). Different combinations of component failures may have dissimilar effects on the performance of a system. Interruption for repair is more prevalent in a WDS at advanced age, and larger systems are more prone to simultaneous pipe failures [1, 2]. Jacobs and Goulter [2] investigated water main failures in the WDS of the city of Winnipeg (Manitoba, Canada) occurred from 1975 to 1984. Analyzing the failure data for the city of Winnipeg, Gheisi and Naser [3] classified the pipe failure combinations into three categories of multi-pipe failure, one-pipe failure and no-failure. They indicated that the

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WDS was in multi-pipe, one-pipe and no-failure situations at 78.5, 9 and 12.5 percent of the times, respectively. This study applies a multi-criteria decision analysis (MCDA) to rank a set of WDS layouts (alternatives) using various states of reliabilities (attributes). The multi-state reliability assessment (MSRA) considers the relative importance of each state of reliability in finding the most reliable system by applying subjective, objective, and dependency weights.

2. Methodology

MCDA approach is applied to MSRA of a set of distribution systems. Zeroth, first, and second state of reliability are considered in decision making procedure. Moreover, flow entropy is applied as the representative of higher states of reliability [4].

2.1. Zeroth state of reliability

This study applies the technique initially proposed by [5] and applied later by others [1, 6, 7] for reliability assessment of a WDS. Following [7], this research measured the zeroth-state reliability (R^0) of a WDS as a weighted mean of performance indices (PIs) of the system. Thus,

$$R^0 = PI(0)\cdot P(0) + \sum_{a=1}^{N} PI(a_1)\cdot P(a_1) + \sum_{a=1}^{N-1}\sum_{b=a+1}^{N} PI(a_1,a_2)\cdot P(a_1,a_2) + \frac{1}{2}\left(1 - P(0) + \sum_{a=1}^{N} P(a_1) + \sum_{a=1}^{N-1}\sum_{b=a+1}^{N} P(a_1,a_2)\right) \tag{1}$$

where N is the number of pipes in the system. $PI(0)$, $PI(a_1)$, $PI(a_1,a_2)$, $PI(a_1,a_2,a_3)$, $PI(a_1,a_2,a_3,\ldots)$ corresponds to the system performance indices when zero, one, two, three, and more pipes are unavailable simultaneously. $P(0)$, $P(a_1)$, $P(a_1,a_2)$, $P(a_1,a_2,a_3)$ are the weighting coefficients defined as the probability that a WDS may end up in a specific failure combination. $P(0)$ is the probability of no failure and $P(a_1)$, $P(a_1,a_2)$, $P(a_1,a_2,a_3)$, and $P(a_1,a_2,a_3,\ldots)$ are the probabilities of one, two, three, and more than three simultaneous failure, respectively.

2.2. First state of reliability

The first state of reliability (R^1) measures the capability of a system to do its task when at least one component is out of service [8]. It is estimated by [6, 9]:

$$R^1 = \frac{R^0 - P(0)\cdot PI(0)}{1 - P(0)} \tag{2}$$

2.3. Second state of reliability

The second state of reliability (R^2) measures the probability that a WDS deliver the demands when at two simultaneous pipe failure occur. It is determined using weighted mean of system's PIs for typical failure combinations [1, 3, 6, 7]. Given "F" as the number of component failure combinations, R^2 is developed as:

$$R^2 = \frac{\sum_{j=2}^{F}\left[\sum_{a_1=1}^{N-j+1}\sum_{a_2=a_1+1}^{N-j+2}\cdots\sum_{a_j=a_{j-1}+1}^{N} PI(a_1,\ldots,a_j)\cdot P(a_1,\ldots,a_j)\right]}{1 - P(0) - \sum_{a_1=1}^{N} P(a_1)} + \frac{1}{2} - \left[\frac{\sum_{j=2}^{F}\left[\sum_{a_1=1}^{N-j+1}\sum_{a_2=a_1+1}^{N-j+2}\cdots\sum_{a_j=a_{j-1}+1}^{N} PI(a_1,\ldots,a_j)\right]}{2\left(1 - P(0) - \sum_{a_1=1}^{N} P(a_1)\right)}\right] \tag{3}$$

2.4. Statistical flow entropy

Shannon [10] introduced the concept of entropy as a measure of uncertainty. Awumah *et al*. [11] applied the concept to assess redundancy and flexibility of a WDS. Knowing the flow and its direction in each pipe, the entropy function is written as [12]:

$$\frac{S}{K} = -\sum_{j \notin I} (Q_j/T)\ln(Q_j/T) - \frac{1}{T}\sum_{j=1}^{J} T_j\left[(Q_j/T_j)\ln(Q_j/T_j) + \sum_{i \in N_j}(q_{ij}/T_j)\ln(q_{ij}/T_j)\right] \tag{4}$$

where S is the information entropy (*nat*); K is the Boltzman constant often taken as 1 (*nat*); T is the total amount of water supplied by reservoir (cms); T_j is the total pipe discharge reaching node j (cms); Q_j represents the demand or supply for node j (cms); q_{ij} is the amount of flow discharge in pipe ij (cms); I represents the set of nodes consisting of source nodes; J is the number of nodes; and N_j means all the upstream nodes directly connected to node j.

2.5. Multi-criteria decision analysis (MCDA)

An MCDA assigns proper weights to decision criteria. The weights are subjective, objective, dependency and combinative weights. Subjective weights are commonly chosen based on the judgment and expertise of the decision makers. Statistical flow entropy method is applied to assign the objective weights to each attribute. Dependency weight lessens the effect of probable correlation that may exist among criteria [13]. Combinative weights consider all subjective, objective, and dependency weights simultaneously [13].

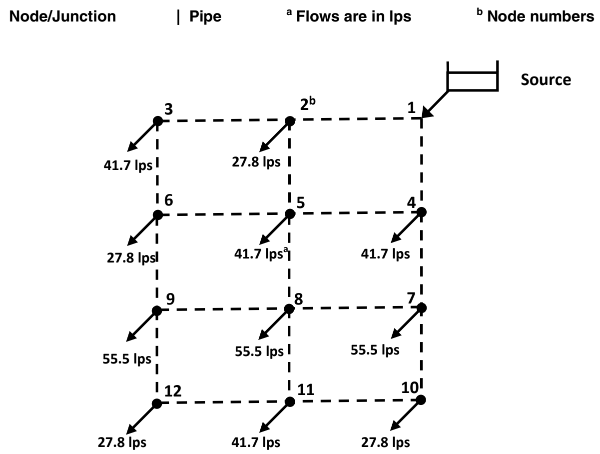

Fig. 1. A schematic view of the hypothetical WDS studied in this paper [12].

3. Test Case

Following [11, 12, 14], this research studies a hypothetical WDS (Fig. 1) and its design layouts (Fig. 2). Pipe diameters vary from 100 mm to 405 (Table 1). Each pipe is 1 km long with a Hazen-Williams coefficient of 130. The piezometric head at node 1 is 100 m. The minimum residual head to meet the demands is set at 30 m. Surface topography is ignored. The modified version of EPANET2 [15] simulates the systems' hydraulics.

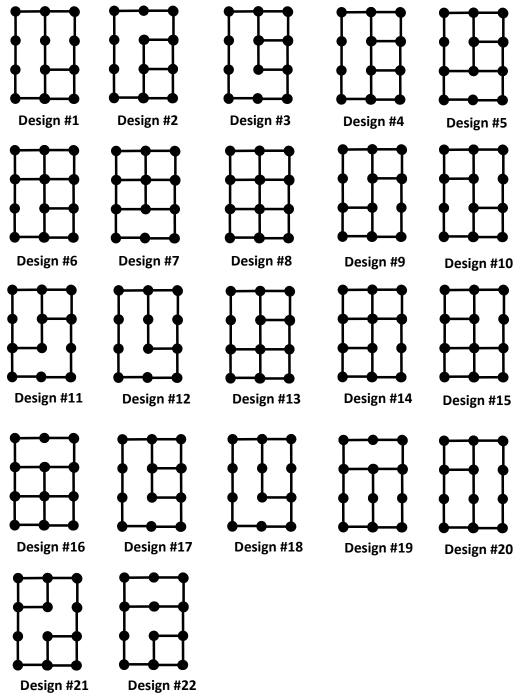

Fig. 2. Set of 22 designs derived from the hypothetical WDS [12].

4. Results and Discussion

Table 2 indicates the objective weight to each attribute. Clearly, the minimum weight is associated to the zeroth state of reliability. The weights increase by increasing the state of reliability with the highest weight for flow entropy of the systems. Results of assigning weights to attributes using entropy approach reveal that higher states of reliabilities have more contribution in reliability ranking than the lower states. Subjective weights are not assigned due to lack of information about type and number of failure that my happen in practice. Following [13], the dependency weights are also computed based on the amount of correlation that exists among the attributes and the results are given in Table 2. Clearly, the zeroth state reliability has the highest dependency weight.

The dependency weights are smaller for entropy, R^2 and R^1 reliabilities. Table 2 also reveals the overall weight computed by combining assigned weights. Clearly, the higher overall weights are assigned to higher states of reliabilities. This implies that the higher state of reliability should have more contribution in decision making process in reliability assessment of WDS. This is important finding since researchers often consider one pipe failure at a time and they believe that the chance of failure of more than one pipe at a time in the system is very little [16, 17].

Finally using the overall weights and three MCDA methods of weighted sum model (WSM), weighted product model (WPM) and technique for order of preference by similarity to ideal solution (TOPSIS), the layouts for the test case are ranked. Table 3 shows the results compared with the results of ranking using reliability or entropy technique. Evidently, the results of MCDA are very different, but they are more comprehensive since considering various states of reliability at the same time.

Table 1. Diameter of pipes for the case study [12].

	Diameter for the pipes connecting the following nodes (*mm*)																
Design #	1-2	1-4	2-3	2-5	4-5	4-7	3-6	5-6	5-8	7-8	7-10	6-9	8-9	8-11	10-11	9-12	11-12
1	348	310	266	226		289	238		189	186	185	213		202	143	105	177
2	284	368	268		225	286	240		188	184	184	215		200	143	105	176
3	328	335	275	169	174	272	248		189	174	259	225			229	143	151
4	326	336	265	185	186	270	237		221	161	177	212		213	130	100	180
5	298	360	223	191	190	298	184		229	166	219	139	227		191	182	100
6	310	354	206	227	226	265	160	209	209	157	172	231		200	123	139	157
7	294	365	194	214	212	291	141	181	206	154	216	190	194		188	185	100
8	302	361	192	228	226	275	138	175	239	179	169	182	178	184	119	162	135
9	325	337	227	231	232	234	190		293		185	149	194	178	139	149	147
10	353	307	225	273		286	187	181	178	182	184	227		190	142	135	159
11	315	345	231	210	210	265	195		260		226	156	211		198	175	109
12	350	309	275	214		289	249		165	200	257	226			227	145	147
13	307	355	221	208	206	282	182		255	188	172	137	204	189	124	150	147
14	318	346	197	246	247	233	146	182	270		184	197	160	170	139	162	133
15	345	319	205	276		299	159	153	207	210	177	179	178	177	133	158	137
16	231	404	210		275	295	162	152	206	206	176	181	176	175	133	158	137
17	361	314	266	245	251	162	238		315	276	276	214			248	113	180
18	405	236	267	308		208	240		283	238	269	217			241	124	170
19	251	390	232		302	244	193	182	223		199	233		163	163	146	148
20	375	274	227	302		249	189	183	223		204	230		162	166	145	149
21	323	336	227	227		318	190	190		226	195	235		164	159	148	147
22	250	390	231		225	315	192	189		224	194	236		163	159	148	147

Table. 2. Assigned weight to each criterion.

	0^{th} Reliability	1^{st} Reliability	2^{nd} Reliability	Entropy
Dependency Weights	0.422602078	0.157749686	0.174032631	0.245615606
Objective Weights	1.56417E-06	0.084376604	0.375269504	0.540352327
Overall Weights	0.001104594	0.156743709	0.347201686	0.494950011

5. Conclusions

In this study, the multi-criteria decision analysis approach is applied to rank a set of distribution layouts (alternatives) using various states of reliabilities (attributes). Both subjective and objective weights of attributes are applied reflecting the relative importance of each state of reliability in decision making process. Results of weighting assignment to attributes show that the higher overall weights are related to higher states of reliabilities. It reveals that higher state of reliability should have more contribution in reliability assessment of distribution system. Researchers have mainly considered one pipe failure at a time when assessing WDS reliability as they believe that the chance of failure of more than one pipe at a time in the system is very little. The methodology introduced in this study using MCDA approach and considering various states of reliabilities instead of just considering one state can be applied as a more comprehensive approach in reliability assessment of water distribution systems.

Table. 3. Reliability ranking of distribution systems' layouts based on different states of reliability, entropy and three MCDA techniques.

Design Number	Rank # (0^{th} Reliability)	Rank # (1^{st}Reliability)	Rank # (2^{nd}Reliability)	Rank # (Entropy)	Rank # (WSM)	Rank # (WPM)	Rank # (TOPSIS)
1	15	17	16	18	16	16	16
2	22	20	18	18	20	20	20
3	8	15	12	21	18	18	19
4	7	10	10	11	10	10	11
5	16	9	9	10	9	9	9
6	1	3	3	2	3	3	2
7	14	6	5	5	5	5	5
8	9	1	1	1	1	1	1
9	4	8	8	9	8	8	8
10	21	11	11	12	11	11	12
11	17	13	13	13	13	13	13
12	10	21	21	22	22	22	22
13	5	4	4	4	4	4	4
14	2	2	2	3	2	2	3
15	3	5	7	7	7	7	7
16	6	7	6	7	6	6	6
17	19	19	20	6	12	12	10
18	20	22	22	20	21	21	21
19	11	12	14	14	14	14	14
20	18	16	17	14	17	17	17
21	13	18	19	14	19	19	18
22	12	14	15	14	15	15	15

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